SESSION VI: PLUME CONTROL—ON-THE-GROUND EXPERIENCE

Phytoremediation at Aberdeen Proving Ground, Maryland: O&M, Monitoring, and Modeling

Steven Hirsh, EPA Region 3

Steven Hirsh described a phytoremediation project that has been initiated at the Aberdeen Proving Ground, a site that has conducted chemical warfare research since 1917. Prior to the 1960s, Hirsh said, munitions, laboratory wastes, and solvents were dumped at the site's burn pits and ignited. A contaminated groundwater plume has formed below the pits, and is discharging to a fresh-water marsh and the Chesapeake Bay. Hirsh said that contaminant concentrations are very high. For example, 1,1,2,2,-tetrachloroethane has been detected in groundwater at 390,000 ppm and TCE is present at 93,000 ppm. Hirsh said that the surficial aquifer is about 30 to 40 feet thick, has a thick confining unit, consists mostly of silty sands, and has a conductivity of about 1 foot per day.

Hirsh said that two objectives were identified for managing the plume—reducing VOC mass and achieving hydraulic control—and that a variety of remedial technologies were evaluated as potential solutions, including hydrogen release compounds (HRC™), *in situ* chemical reactions, monitored natural attenuation, recirculating wells, and phytoremediation. Significant interest was generated in the latter; therefore, about 200 hybrid poplars have been planted in a horseshoe shape at the site. Before the trees were planted, Hirsh said, an agronomic assessment was performed, a drainage system was installed to divert rainwater off of the burn pits, and monitoring wells were installed. The trees were installed by Applied Natural Sciences, Inc., he said, using techniques that promote vertical root growth. Boreholes were augered, plastic sleeves were installed, two-year-old trees were planted, and boreholes were backfilled. Hirsh said that excavation activities were performed last year to evaluate root growth. For the most part, very little horizontal growth was observed, and the roots appeared to be bound within the borehole. Hirsh said that the trees are growing well at the site, noting that they were about 30 feet tall in 1999. The site was hit by a hurricane in the fall of 1999 and this caused about 30% of the trees to lean over, Hirsh said, but site managers have straightened them.

Hirsh said that groundwater samples are being collected, but that it is too early to determine whether the trees are reducing contaminant concentrations at this site. He said that a number of other parameters are also being monitored to determine how much groundwater the tree plantation is removing from the plume. For example, data are being collected on leaf area, tree diameter, land area, sap flow rates, and a variety of climatological parameters, such as temperature, relative humidity, solar radiation, and wind speed. These data are then used, Hirsh said, to calculate PET and crop coefficients. Based on the calculated values, researchers estimate that each tree is currently taking up about 8 gallons of water per day, and that this value will grow to 12 gallons per day once the canopy closes. Extrapolating, Hirsh said, this suggests that the mature plantation will pump about 2,000 gallons per day. He said that this is only about one-fifth of the pumping rate that is needed to achieve hydraulic control at this particular site.

Hirsh said that transpiration gas is being measured at the site, and that 1,1,2,2-tetrachloroethane and TCE have been detected as offgassing products in at least a couple of trees. (Gases were measured by placing bags over leaves and sealing them. Cold traps were added to some of the bags, but investigators found that these devices had minimal impact on gas measurements.) Hirsh said that flux chambers have also been established to determine whether contaminants are offgassing from soils. Some TCE has been detected in the chambers. Fourier transform infrared (FTIR), another air sampling technique, is also being used to determine whether the plantation, as a whole, is emitting VOCs to the environment at dangerous levels. Results collected to date indicate that this is not the case.

Hirsh said that site managers at the Aberdeen Proving Ground know that phytoremediation systems do raise some ecological concerns. Therefore, soap has been hung on the poplars to deter herbivores from feeding on them. In addition, efforts are being made to determine whether soil functioning is adversely impacted when contaminated leaves degrade on the ground. For example, Hirsh said, nematode populations are being evaluated. Honeybee hives are also being monitored to determine if volatiles are accumulating within them.

Hirsh closed his presentation by talking about modeling efforts that have been performed for the site. He said that these were run under the assumption that phytoremediation, recirculating wells, and natural attenuation would all be working in concert. According to MODFLOW, he said, phytoremediation should have a significant effect on the top portions of the aquifer, but the impact will decrease in deeper layers. He said that three-dimensional modeling was performed so that researchers could estimate how much contaminant would be removed by each technology. Results indicated that 400 pounds would be degraded through phytoremediation, 1,500 pounds by microbial degradation, and 1,950 pounds removed by recirculating wells.

Phytoremediation Systems Designed to Control Contaminant Migration
Ari Ferro, Phytokinetics

Ari Ferro said that researchers believe that tree plantations can be used to prevent subsurface contaminants from migrating. In fact, he said, this theory is currently being tested at a site in Ogden, Utah. The site, Chevron's Light Petroleum Products Terminal, has a dissolved-phase TPH plume located about 6 to 8 feet bgs. (Concentrations have been detected between about 5,000 parts per billion [ppb] and 10,000 ppb.) In April of 1996, Ferro said, a dense stand of hybrid poplar trees was planted perpendicular to groundwater flow. (The design has three rows of poplars. There are about 6.5 feet between rows and about 7.5 feet between trees.) Ferro described the planting method that was used at the site: 8-foot deep boreholes were drilled, long poplar cuttings were placed into the holes, and the holes were backfilled with sand and peat. Ferro said that the trees were planted directly into the saturated zone; thus, from the start, the trees used subsurface groundwater as their water source rather than relying on surface irrigation. Growth has been robust, he said, and the trees are approaching canopy closure. Ferro said that the root structure for one tree was analyzed at the end of the third growing season. A dense proliferation of roots, many extending into the saturated zone, was observed in and around the borehole. Interestingly, the deepest roots did not come from the tree's original pole, which was dead; instead, the deepest roots originated from highly branched roots that were located nearer to the surface.

Ferro said that researchers have generated estimates on the amount of groundwater that is being used by the tree plantation. He said that each tree pumped about 0.25 gallons per day during the second growing season, that this value rose to 11.9 by the fourth growing season, and that it is expected to increase to 17.7 by the end of the fifth season. Ferro said that these values represent the volumetric water used by trees (V_t) minus the amount of precipitation that falls during a growing season. Both parameters have been measured directly at the site; precipitation is measured at an onsite weather station, and V_t is quantified using thermal dissipation probes that measure sap flow. V_t values can also be determined indirectly, Ferro said, using calculations that have the following inputs: PET, crop coefficient, leaf area index, and tree stand area. Ferro said that investigators did use calculations to estimate V_t, and that the results obtained were similar to those identified through direct measurements.

Ferro said that five piezometers have been installed at the Ogden, Utah, site. Some are located upgradient of the trees, some are in the middle of the plantation, and others are downgradient. These were sampled several times between May 1998 and August 1999, and TPH, BTEX, and water levels were measured. The results indicate that contaminant concentrations decrease as groundwater moves through the tree stand. As for water-level measurements, Ferro said, groundwater was not shown to dip during the growing season and this surprised site investigators. (Based on their calculations, researchers expected to find that the trees transpired a volume of water equivalent to an 11-foot thickness of the saturated zone. Using estimated V_t, crop coefficient, and leaf area index values for the fourth growing season, researchers determined that the tree stand would transpire about 480 gallons of groundwater per day. To determine whether transpirational water use by the trees would be significant relative to the total flow of groundwater, researchers used Darcy's Law to calculate the approximate volume of water that flows beneath a vertical cross-section of the site. The rate of groundwater flux through a 1-foot thick vertical cross-section was calculated to be about 44 gallons per day.) Ferro said that he is not sure why water-level measurements failed to show a dip; efforts are underway to identify plausible explanations.

Before closing, Ferro described a phytoremediation project that has been proposed for the Bofors-Nobel Superfund site in Muskegon, Michigan. This site, placed on the NPL in 1989, produced industrial chemicals between the 1960s and 1980s and disposed of waste sludge into 10 lagoons. The lagoons have been drained, Ferro said, but the sludge that remains is highly contaminated with 1,2,4-trichlorobenzene, 3,3,-dichlorobenzidine, 2-chloroanaline, and a variety of other contaminants. Ferro said that site managers want to plant deep-rooted trees in the lagoons in an effort to reduce leachate formation, stabilize contaminants, and promote rhizosphere degradation. The proposal also recommends planting trees and native grasses in the areas between the lagoons in an attempt to minimize rain-water infiltration. In addition, a poplar stand is proposed in another portion of the site to intercept groundwater flow, and revegetation has been proposed for a 9-acre segment of the site. Ferro said that predesign studies are being performed, noting that a small field study was initiated in 1999 to evaluate which planting methods would be best to use and which plants are most tolerant of the site's toxic sludges. He said that a greenhouse study will be initiated in the near future.

Deep Planting
Edward Gatliff, Applied Natural Sciences, Inc.

At most sites, Edward Gatliff said, 80% to 90% of tree roots develop within the first 3 feet of soil. If enough precipitation falls upon a site, he said, roots will not have an incentive to grow much deeper. Thus, Applied Natural Sciences, Inc., has developed "deep planting" techniques to coax plant roots to grow deeper and to tap into aquifers or horizon soils that lie deeper than 3 feet. By using this approach, Gatliff said, site managers can be assured that roots will come into contact with targeted subsurface areas. Gatliff said that Applied Natural Sciences, Inc., developed its first "deep planting" technique in 1990, while working on a site in New Jersey, which had a contaminated aquifer that was located about 16 to 20 feet bgs. Investigators considered using alfalfa to tackle the deep contamination at this site, but soon realized that the site's soil had too much clay for alfalfa roots to penetrate. So, they started experimenting with trees. Since that time, Gatliff said, Applied Natural Sciences, Inc., has identified several types of "deep planting" techniques that can be used. Some of these have been patented.

Gatliff described the process involved with "deep planting." If the top 5 to 10 feet of subsurface are targeted in a phytoremediation project, he said, trees can be installed using a trenching technique. For deeper depths, however, boreholes are drilled, trees are placed inside, and the boreholes are backfilled. Gatliff said that the borehole diameter and depth dictates the type of drill rig that must be used. For example, a three-point auger or a tractor can be used to install boreholes to depths less than 5 feet, but a skid steer with an auger extension is needed to install boreholes up to 10 feet deep. For holes that are drilled between 10 and 20 feet deep, a medium-sized drill rig with an 8-foot stroke can be used, but anything deeper requires a caisson rig. Gatliff said that casings are usually installed in the boreholes, noting that these help to limit preferential shallow root development and surface-water short-circuiting. He said that Applied Natural Sciences, Inc., has experimented with three different kinds—ADS and metal casings, sonotubes, and plastic casings—and found that each has pros and cons. In general, Gatliff prefers plastic casings, because these are cheap and easy to use. He said that casings do not have to be installed in the boreholes, but said that roots have been shown to develop in surficial areas when casings were not included. He said that this does not hold true for all sites, noting that roots grow deep in uncased boreholes that are drilled in areas that have high clay content. Gatliff said that Applied Natural Sciences, Inc., has not yet determined the optimal diameter for boreholes, but believes that they should be greater than 16 inches. At many sites, good results have been obtained with 18-inch boreholes. Gatliff said that trees planted in boreholes can be planted with the rootballs either near the surface or deeper in the subsurface. If the latter approach is used, roots reach targeted depths more quickly and trees are less likely to require irrigation, because their roots tap into groundwater almost immediately.

Gatliff said that trees that have been installed with “deep planting” techniques have been shown to remediate contaminants. For example, at a site in Finley, Ohio, TCE concentrations decreased significantly after a plantation was installed. Trees at this site are clearly tapping into groundwater sources, he said, noting that the trees were unaffected by a serious drought that recently impacted the region.

Gatliff said that he does not know what the depth limitations are for “deep planting” techniques. At some sites, trees have been installed in boreholes that reach 35 feet deep. At the ANL-E site’s 317/319 area, he said, Treewells® have been planted in 30-foot-deep boreholes. The Treewell® design, Gatliff said, uses elongated roots, which are pregrown and attached to rootballs. At ANL-E, rootballs were placed about 5 to 10 feet bgs and elongated roots were suspended another 2 to 8 feet. Gatliff said that it may be possible to design systems that penetrate even deeper. For example, he said, acacia trees have been known to extend roots as deep as 100 feet bgs. Roots that grow in sewers have been reported to reach lengths greater than 200 feet.

Gatliff provided rough estimates of the costs that are associated with “deep planting” techniques:

System Description	Costs Per Tree	Costs Per Acre
Target depth of 10 feet	\$100 to \$300	\$20,000 to \$60,000
Target depth of 10 to 20 feet	\$250 to \$500	\$50,000 to \$100,000
Target depth of > 20 feet	\$500 to \$1,500	\$100,000 to \$300,000

He said that costs can be controlled by using the right methodologies and equipment for a particular site.

Transpiration: Measurements and Forecasts
James Vose, U.S. Forest Service

James Vose opened his presentation by clarifying the definitions of “transpiration” and “evapotranspiration,” two terms, he said, that are often used interchangeably. Vose said that transpiration represents the amount of water that trees take up and release to the atmosphere. Evapotranspiration represents transpiration plus evaporation (*i.e.,* the free water in soils and on the surface that undergoes a phase transformation to water vapor). Vose said that the evaporation component is small compared to the transpiration component. Therefore, he focused on transpiration. He described the controlling factors. Climate plays a large role: temperature, solar radiation, vapor pressure, wind speed, and precipitation affect how much water a plant transpires. Also, he said, plant physiology, including stomatal conductance, xylem anatomy, rooting depth, sap wood quantities, and sap wood flow rates, dictate how much water is used. To demonstrate his point, Vose presented a graph that showed that transpiration rates generally increase with increasing sap wood quantities. He asked attendees to note, however, that plant species that have the same quantities of sap wood do not all have the same transpiration rates. This is due, in part, to the fact that plants have different anatomies, which affects how water flows through their sapwood. Vose said that leaf area index and leaf distribution also exert great influence on transpiration rates. In addition, site characteristics play an important role, Vose said, noting that a plant’s capability to draw water into its roots is influenced by the accessibility of groundwater sources, the site rooting volume, and the soil water holding capacity.

Vose described the methods that can be used to estimate transpiration rates. At the tree level, he said, transpiration can be measured using weighing lysimeters, leaf-level measurements, and sap flow probes or collars. Once transpiration rates are established for an individual plant, Vose said, these rates are used to extrapolate rates for entire tree stands. He warned, however, that several assumptions must be made to perform the extrapolations, and said that this could compromise the accuracy of predictions. Vose said that there are ways to measure tree stand transpiration rates directly, such as the eddy flux or gauged water shed methods, but said that these techniques do have limitations. For example, both techniques measure whole-system response; thus, it is difficult to determine how much transpiration is coming from trees *versus* herbaceous cover. Vose said that a variety of models, ranging from simple empirical models to complex mechanistic ones, are also available to help investigators predict transpiration rates.

Vose described one site, located in Fort Worth, Texas, that initiated a phytoremediation project in 1996. Whips and one-year-old eastern cottonwoods were planted at this site in an effort to intercept a TCE plume. Starting in 1997, Vose said, data have been collected for a variety of parameters, such as leaf water potential, stomatal conductance, soil moisture release, and climatic conditions. In addition, collars and probes were installed to collect monthly sap flow measurements from about 16 cottonwoods. (More than one probe was used on each tree.) Vose said that the data collected were used to calculate transpiration, and he presented what has been learned over the last few years. He said that transpiration rates in the one-year-old trees were higher than those measured in the whips during the first year of growth, because the former were larger. However, he said, when investigators standardized for tree size, they found that the whips actually had higher sap flow rates. By the end of the second year, Vose said, transpiration rates in the one-year-old trees and the whips were about 6 gallons/day/tree and 1.6 gallons/day/tree, respectively. Vose said that investigators also used PROSPER, a model that has been in existence for about 25 years, to estimate transpiration rates at the site. Initially, he said, the model appeared to do a good job of simulating transpiration; modeled data were in good agreement with measured data. By the second year, however, correlations were not as strong, and modeled estimates diverged significantly from measured values during the driest months of the year. Over the next year, Vose said, he hopes to improve the PROSPER model.

Vose said that extrapolations were made on the measured and modeled data to predict how much water might be transpired across the Fort Worth, Texas, site in future years. Predictions ranged from 500,000 to 2,000,000 gallons/hectare/year. The lower bound, he said, represents what PROSPER estimated as the transpiration rate at a 15-year-old plantation. The upper bound, he said, represents projected transpiration rates in a mature open forest. The rates would be closer to about 1,000,000 gallons/hectare/year, Vose said, if investigators accounted for the shading that will result in a closed canopy situation. Vose said that it is useful to make predictions using a wide variety of methods, because it helps investigators determine the outer boundaries for possible transpiration rates. He is hopeful that models will be improved significantly in the future so that more accurate predictions can be made.

Speaker Panel and Audience Discussion

Audience members asked questions or provided comments about the following topics:

- *Red cedar juniper trees*. Fletcher noted that red cedar junipers, which are evergreens, are growing at the Fort Worth, Texas, site. He said that he thinks these trees might be desirable to use in phytoremediation designs, and asked Vose whether he plans to model performance of these trees. Vose said that he had not planned to do that for this site, but did agree that sites in the Southwest might benefit from having a mixture of conifers and hardwood in their remedial designs.

- *The suitability of using poplars and willows over wide geographical ranges.* J.G. Isebrand, who serves on the International Willow and Poplar Commission, said that it is his job to ensure that willow and polar cultures are exchanged responsibly. He said that he was delighted to learn about the different ways in which these trees are being used in phytoremediation projects. He did caution, however, that trees can fail if they are planted in inhospitable soils or in regions where the trees are prone to disease. He asked meeting attendees to keep this in mind, noting that all efforts should be made to avoid failures—even just a little negative publicity could set back the acceptance of phytoremediation.

- *Biochemical parameters that impact transpiration rates.* McMillan noted that Vose's presentation focused on physical parameters that control transpiration rates. He asked whether biochemical parameters, which have been discussed in the European literature, might also have an influence. Vose said that this could be, but that he was not aware of any that played a significant role. In general, he said, water uptake processes are really dominated by physical processes (*e.g.,* resistances and differences in potentials), as well as anatomical features (*e.g.,* number of stomata, distribution of stomata, amount of sap wood). He said that biophysical processes do control how water is pumped at the cellular level, but speculated that the influence on overall water usage is only minimal.

- *Poplar tree costs*. One meeting attendee asked how much poplar trees cost. Gatliff said that trees cost about $10 to $20, but that whips can be obtained for about $1 to $3.